FINAL TECHNICAL REPORT

QUATERNARY FAULTING OF THE GREATER MONTEREY AREA, CALIFORNIA

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FOR

PANSY R. YEATTS
CONTRACTING OFFICER
U.S. GEOLOGICAL SURVEY

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ABSTRACT

The greater Monterey area has experienced rapid development as the population of the San Francisco Bay region has spread southward. Because no large earthquake has seriously affected this area since the 1926 M 6.1 Monterey Bay doublet, little attention has been focused upon seismic hazards. This study involved detailed investigation and evaluation of Quaternary faulting, determining subsurface geometry and continuity of onshore faults, and preparing a seismic hazard fault map.

Field mapping and subsurface analyses revealed that the Seaside, Ord Terrace, and Chupines faults extend from the coast southeastward into the Laguna Seca area. Field investigation and air photo interpretation established that late Pleistocene terrace deposits and Holocene colluvium are offset by thrust faults near Monterey and by through-going, near-vertical faults in Carmel and in Carmel Valley. Radiocarbon dating indicates movement along the Tularcitos fault within the past 7,780 years, along the Sylvan thrust within the past 4,890 years, and probable movement along the Hatton Canyon fault within the past 2,080 years.

Late Quaternary deformation is indicated by late Pleistocene terrace deposits tilted by as much as 22 degrees and by folded Pleistocene terrace deposits. Quaternary fault slip rates average about 0.11 mm/yr. Although earthquake focal mechanisms are poorly constrained by a lack of offshore seismographs, they indicate right-lateral strike-slip on northwest-striking vertical faults. Interpretation of field mapping, drill hole data, and focal mechanisms suggests that the shorter, discontinuous thrust faults splay off of the longer, through-going strike-slip faults.

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INTRODUCTION

General Statement

The greater Monterey area has experienced rapid cultural development as the population growth of the San Francisco Bay region has spread southward. With the conversion of the Fort Ord Military Reservation into the California State University at Monterey Bay, this growth will accelerate soon. Because no large earthquake has seriously affected this area since the Monterey Bay doublet (M=6.1) of 1926, little attention has been focused upon its seismic hazards.

The study area includes the Monterey Peninsula and the lower Carmel Valley areas (figure 1). Geologically, this area is critically situated within the complexly deformed Salinian block between the active San Andreas fault to the northeast and the San Gregorio fault zone to the southwest (figure 2). It also is characterized by compressional tectonics related to the San Andreas fault system and includes many poorly understood subsidiary faults (Greene and others, 1988). The activity of these subsidiary faults is difficult to assess; however, the 1971 San Fernando Valley, 1982 Coalinga, and 1994 Northridge earthquakes are important reminders of the potential seismic hazard of these lesser faults.

Preliminary geologic mapping (Clark and others, 1974) suggested that several faults in the study area were potentially active. Bryant (1985) reviewed published mapping, performed a limited reconnaissance of the area, and concluded that previously mapped faults were "not sufficiently active" to require zonation by the State Geologist. However, analysis of Quaternary mapping by Dupré (1990b); recent detailed mapping and trenching by geotechnical consultants; unpublished mapping by Clark; and investigation of earthquake and landslide hazards of Carmel Valley by Rosenberg (1993) suggested recent faulting, the extent and nature of which was previously unrecognized.

Therefore, the purposes of this study were to evaluate Quaternary fault offsets, determine the extent and geometry of fault movement, and prepare a seismic hazard fault map. These results will provide a model for a better understanding of the nature of similar, lesser known faults of the Salinian block. Additionally, these results will directly influence land use planning in Monterey County concerning existing and potential seismic hazards.

Methods of Investigation

Assessing the extent and activity of Quaternary faulting requires a critical evaluation of Quaternary offsets suggested by published and unpublished mapping. To accomplish this goal, our investigation included the following major work tasks:

1. Detailed investigation and evaluation of Quaternary faults in the greater Monterey area:

   - Reviewing pertinent literature related to the geologic, soil, and hydrologic conditions in the study area and surrounding region. Sources of data included government agencies (U.S. Geological Survey, California Division of Mines and Geology, USDA Soil Conservation Service, Monterey Peninsula Water Management District, Monterey County Water Resources Agency, Monterey County Public Works Department, and the Monterey County Planning Department); unpublished theses and dissertations; and geotechnical consultant reports.

   - Site analysis with aerial photographs ranging in age from 1930 to 1990. These photographs ranged in scale from 1:15,840 to 1:58,000, and included natural color, infrared, and black and white imagery.

- Detailed logging of seven critical exposures.
- Field mapping to provide additional information in areas of significant data gaps.
- Collecting and submitting carbon-bearing samples of colluvium for radiocarbon dating.

2. Determining the subsurface geometry and continuity of onshore faults in the greater Monterey area:
   - Using lithologic and electric logs of approximately two hundred wells to determine the geometry and continuity of concealed fault segments in the Seaside and Monterey coastal areas and in Carmel Valley.
   - Examining the recent offshore seismic interpretations of Gardner-Taggart and others (1993) and H. Gary Greene in southern Monterey Bay for possible continuity of the active Monterey Bay fault zone with onshore strands as constrained by drill hole data.
   - Conducting detailed surface mapping and analysis of geomorphic features to determine the relationship of onland low-angle thrust faults to more through-going strike-slip faults.
   - Interpreting fault geometry below the depths of well control using both surface and depth distribution of earthquakes.
3. Preparing a seismic hazard fault map showing the location and activity of fault segments:
   - Meeting several times with the Monterey County Planning Department to discuss their needs as nontechnical map users.
   - Plotting data collected in this study at a scale of 1:24,000 on a base map suitable for non-technical users.

Accompanying this report are four oversize map sheets. Plate 1 shows subsurface structural contours on the top of the Monterey Formation. Plates 2 and 3 show faults, folds, epicenters, and locations of Quaternary deformation in the Monterey and Seaside 7.5-minute quadrangles. Plate 4 shows the location and relative activity of these faults on a cadastral base map.

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STRATIGRAPHY

General Statement

Resting nonconformably upon Salinian basement is an incomplete stratigraphic section ranging in age from Paleocene to Holocene and having a composite thickness of as much as 1,920 m. Locally, the Paleocene rocks are intruded by Oligocene basaltic andesite.

Salinian Basement

Paleozoic(?) biotite quartzofeldspathic schist and Cretaceous granodiorite form the basement in the study area. Schist outcrops known as the schist of the Sierra de Salinas (Ross, 1976), are rare and restricted to a small area north of the Laureles fault. Granitic rock intrudes the schist in the Salinian Block; this relationship is well exposed on the east side of Laureles Grade.

Porphyritic granodiorite crops out on the Monterey Peninsula west of the Navy fault zone. East of the Navy fault, exploratory wells reached granitic basement at nearly 600 m below sea level. Compton (1966) estimated the granitic rock in the northern Santa Lucia Range to be as much as least 3 km thick. Radiometric dating indicates an age of 95–83 Ma for the granitic basement in the northern Santa Lucia Range (Hall, 1991; plate 2a).

Paleocene-Oligocene Rocks

Nonconformably overlying the basement rocks at Point Lobos and at the northern end of Carmel Bay are Paleocene marine sedimentary rocks known as the Carmelo Formation of Bowen (1965). The Carmelo Formation consists of marine interbedded arkosic sandstone, siltstone, mudstone, and pebble-cobble conglomerate. The Carmelo Formation rests depositionally upon and is locally faulted against the granodiorite. Estimates of thickness range from 220 m (Lawson, 1893) to 430 m (Herold, 1934). Mollusks and foraminifers indicate a Paleocene age for the Carmelo Formation (Bowen, 1965). Clifton (1981) interpreted sedimentary structures and concluded that the Carmelo Formation was laid down by turbidity currents in a submarine canyon.

Around Carmel Bay are scattered flows and flow-breccias of basaltic andesite (carmeloïte of Lawson, 1893). Clark and others (1984) reported a K-Ar age of 27.0±0.8 Ma (Oligocene) for samples from Arrowhead Point and estimated a thickness of 20 m for the carmeloïte. At Palo Corona Ranch, however, the carmeloïte locally appears interbedded beneath middle Miocene sandstone and above arkosic sandstone that is provisionally considered to be Oligocene. The carmeloïte has three structural relationships: unconformably overlying granodiorite, faulted against granodiorite, and intruding the Carmelo Formation.

Middle Miocene Sandstones

A clastic section as much as 260 m thick in the vicinity of Robinson Canyon nonconformably overlies the Salinian basement and underlies the Monterey Formation. The lower part of this section includes non-marine “red beds” consisting mostly of arkosic sandstone, with common conglomerate and siltstone beds. Brown (1962) referred to these as the Robinson Canyon Member of the Chamisal Formation, which Bowen (1965) later formally defined. At the type locality in Robinson Canyon, the red beds are approximately 140 m thick (Bowen, 1965, p. 51). Although the age of these red beds is uncertain, stratigraphic position and regional correlation with similar units suggest that the red beds are middle Miocene (Younse, 1980).

The upper part of this section includes the marine sandstone stratigraphically above the red beds and below the Monterey Formation. The marine sandstone unit consists mostly of arkosic sandstone, with common conglomerate beds, and rare siltstone beds. This marine sandstone is approximately 120 m thick in Robinson Canyon (Bowen, 1965, p. 52). To the west along Potrero Canyon, the red beds are absent, and the sandstone between the granitic basement and the Monterey Formation is as much as 175 m thick and contains middle Miocene foraminifers in the upper part.

Monterey Formation

This formation consists of the siliceous and diatomaceous shale, siltstone, and claystone that stratigraphically overlie the middle Miocene marine sandstones. Within the study area, there are three mappable units of the Monterey Formation (Clark and others, 1974). The lower unit is semi-siliceous mudstone with interbedded siltstone of middle Miocene age. The middle unit is a predominantly hard porcelanite with bentonite interbeds (Aguajito Shale Member of Bowen, 1965) of late Miocene age. The upper unit consists of soft diatomite with chert interbeds (Canyon del Rey diatomite Member of Bowen, 1965) of late Miocene age.

Locally within the City of Monterey, Monterey Formation rests directly on the basement rocks. The Monterey Formation crops out in two main areas: in the hills south of the Carmel River and west of Robinson Canyon, and in the hills north of the Carmel River. North of the Chupines fault zone, the Monterey Formation rarely crops out, but is commonly penetrated in drill holes. Plate 1 shows the top of the Monterey Formation north of the Chupines fault as contoured from well data. Near Carmel Valley, the maximum thickness of the Monterey Formation is about 900 m (Bowen, 1965).

Santa Margarita Sandstone

Conformably overlying Monterey diatomite is a marine and brackish-marine, fine- to coarse-grained arkosic sandstone known as the Santa Margarita Sandstone. Near Laguna Seca, the Santa Margarita sandstone crops out in a narrow band along the Chupines fault. South of the Chupines fault zone, the Santa Margarita Sandstone is absent, but is commonly found in drill holes north of the Chupines fault zone. Logs of water wells show a maximum thickness of approximately 75 m for the Santa Margarita Sandstone in the Seaside quadrangle (Staal, Gardner & Dunne, 1990a). Paleontologic evidence suggests a late Miocene age for the Santa Margarita Sandstone in the Seaside quadrangle (Bowen, 1965).

Paso Robles Formation

Unconformably overlying the Santa Margarita Sandstone is a series of non-marine, fine grained, oxidized sand and silt beds with common gravel beds. Previous workers (Beal, 1915; Herold, 1935) correlated these beds with the Paso Robles Formation of the southern Salinas Valley. Dupré (1990b) preferred not to use the name “Paso Robles,” and instead used the term “continental deposits.”

The Paso Robles Formation is exposed in the foothills of the Laguna Seca area, and is mostly absent south of the Chupines fault zone. Well logs show that the Paso Robles Formation is also present beneath the eolian deposits of the Seaside area. Logan (1982) divided the Paso Robles Formation into four hydrogeologic units; one of which, the “Seaside clay,” is a distinctive blue clay marker horizon. The Seaside clay is approximately 12–21 m thick and easily recognized on well logs.

Herold (1935) estimated the Paso Robles Formation to be as much as 230 m thick in nearby San Benancio Gulch (Spreckels quadrangle). Two deep test holes near Laguna Seca revealed an even greater thickness of the Paso Robles Formation, 335 m, than exposed in outcrop (Staal, Gardner & Dunne, 1991). Stratigraphic position and regional correlation with similar units suggest that the Paso Robles Formation is Pleistocene and possibly Pliocene in part (Dupré, 1990b).

Aromas Sand

Overlying the Paso Robles Formation is a series of eolian deposits known as the Aromas Sand (older eolian deposits of Dupré, 1990b). The stratigraphic relationship of the sediments mapped as Aromas Sand near Salinas is unclear. In some areas, these sediments appear to overlie the Paso Robles Formation with unconformity (Bowen, 1965); elsewhere, the two units may be in part facies equivalents (Dupré, 1990a).

The Aromas Sand is a unit of moderately well sorted sand as much as 60 m thick that contains no intervening fluvial deposits. Several sequences of eolian deposits may be present, each separated by paleosols (Dupré, 1990b). The Aromas Sand crops out on the hilltops of Fort Ord. Well logs show that the Aromas Sand occurs beneath eolian deposits in the Seaside area. Dupré (1975, p. 100) used sea-level fluctuation curves to determine that the Aromas Sand is Pleistocene.

Pleistocene Terrace Deposits

A series of uplifted coastal terraces crops out on the Monterey Peninsula and ranges in altitude from 30 m to 240 m (see table 1). The coastal terrace deposits include both marine sediments and their associated non-marine veneer. Coastal terrace deposits consist of moderately well sorted marine sand containing thin, discontinuous gravel-rich layers; some are overlain by poorly sorted fluvial and colluvial silt, sand, and gravel. These terrace deposits are commonly well indurated in the upper part of the weathered zone; many are capped by maximally developed soils, some having duripans. The thickness of the coastal terrace deposits is variable, but generally less than 6 m (Dupré, 1990b).

Elevated fluvial terraces are exposed mainly on the north side of the Carmel River as discontinuous topographic benches and as remnants capping hilltops. These fluvial terrace deposits consist of a highly variable mixture of moderately to poorly sorted, fine to coarse-grained silty sand with pebble to cobble gravel. The terrace deposits are weakly to moderately cemented, and locally are strongly cemented with carbonate in the upper few meters; some are capped by maximally developed soils, and in places have duripans (Dupré, 1990b). The thickness of the fluvial terrace deposits ranges from 0 to about 17 m (Williams, 1970).

The terrace deposits are Pleistocene, although their absolute ages are unknown. McKittrick (1988) correlated the terraces on the Monterey Peninsula with radiometrically dated marine terraces in Santa Cruz using relative altitude and soil development. Dupré (1990a) used correlation with known highstands of sea level to estimate the age of the terraces. Because the Santa Cruz terraces are separated from the Monterey terraces by significant faults, direct correlations remain uncertain. The fluvial terrace deposits in Carmel Valley presumably correlate with the marine terraces on the Monterey Peninsula (Williams, 1970, p. 52); however, discontinuous outcrops and faults make this connection difficult.

Landslide Deposits

Landslides in the study area range from small, shallow soil slips to deep bedrock slides. Landslides occur in all the geologic units, but are most common in the Monterey Formation. Younger landslides have fresh scarps, disrupted drainages, closed depressions, and disturbed vegetation. Older landslides are modified by erosion, resulting in subdued scarps, reestablished vegetation, and new drainage paths. Soils have formed on some older landslide deposits; however, most soils are poorly developed or absent because of high erosion rates and steep slopes.

Dune Deposits

In the study area, Dupré (1990b) distinguishes three types of dune deposits: late Pleistocene coastal dunes, Holocene Flandrian dune deposits of Cooper (1967), and Holocene dune sand deposits. The late Pleistocene coastal dunes consist of well-sorted, fine-to medium-grained sand deposited in an extensive coastal dune field in the Fort Ord area. The thickness of the late Pleistocene dunes ranges from 2 to 25 m.

The Flandrian dune deposits consist of well-sorted sand as much as to 30 m thick, deposited in a belt of parabolic dunes up to 700 m wide. Johnson (1993) noted a paleosol at the base of the Flandrian dunes near Stilwell Hall (approximately 5 km north of the study area). Dating of charcoal in this paleosol gave ^{14}C ages of 2,130±80 (Lawrence Livermore National Lab sample no. CAMS-4806) and 1,800±60 yr B.P. (Lawrence Livermore National Lab sample no. CAMS-4807) indicating that the Flandrian dunes are late Holocene (Johnson, 1993).

The Holocene dune sand deposits consist of well sorted, fine-to medium-grained sand, deposited as linear strip of coastal dunes near Spanish Bay and Cypress Point. These deposits are as much as 25 m thick.

Flood-Plain Deposits

Older flood-plain deposits are stratigraphically between terrace deposits and younger flood-plain deposits and probably are of Holocene age. Older flood-plain deposits consist of a variable mixture of poorly consolidated, well-drained, moderately to poorly sorted sand and silt with thin clay layers, and minor amounts of gravel (Dupré, 1990b).

The older flood-plain deposits are nearly flat to gently sloping and fill an irregularly shaped valley beneath the Carmel River (Logan, 1983). Interpretation of well log data suggests that the older flood-plain deposits are typically less than 18 m thick in the study area, but locally may be up to 40 m thick.

Holocene age younger flood-plain deposits occupy the Carmel River channel and are less than 6 m thick. These deposits consist of unconsolidated, well-drained, heterogeneous deposits of sand and silt, including relatively thin, discontinuous layers of clay and local gravel deposits (Dupré, 1990b).

Colluvium

Colluvial deposits are common in the hillside areas, especially in topographic swales. These deposits are up to tens of meters wide, hundreds of meters long, and are as much as 7 meters thick. Colluvium consists of a variable mixture of unconsolidated, poorly drained, poorly sorted clayey sand, sandy clay, and gravelly clay with significant amounts (up to 20 percent by volume as visually estimated) of organic debris (Rosenberg, 1993). Dating of the colluvium in the study area has yielded five ^{14}C ages ranging from 1,880 to 7,780 yr B.P.

Undifferentiated Alluvial Deposits

Undifferentiated alluvial deposits of variable thickness and composition fill the channels of the major hillside drainages. These include moderately to well-sorted clean sand, moderately to poorly sorted silty sand with gravel and discontinuous lenses of clay and silty clay, and moderately sorted gravels and cobbles.

REGIONAL STRUCTURE

The Monterey and Seaside quadrangles are approximately 31–38 km southwest of the seismically active San Andreas fault and 6–11 km northeast of the San Gregorio fault zone. These two faults mark the northeastern and southwestern boundaries, respectively, of the Salinian block with its crystalline basement of granitic and regionally metamorphosed rocks.

The San Gregorio and Monterey Bay fault zones, both of which are seismically active, trend southeastward into the area. The Carmel Canyon fault, which strikes N. 30° W. along a tributary to Carmel Canyon, is a fault segment within the San Gregorio fault zone. The San Gregorio fault zone is at least 130 km long and may extend northwestward from Big Sur for about 190 km to join the San Andreas fault at Bolinas (Greene and others, 1973). The Monterey Bay fault zone abuts the San Gregorio fault zone in the northwestern part of Monterey Bay and consists of a discontinuous series of en echelon faults that strike N. 40° W. Individual faults of the latter zone continue onshore in the Seaside/Monterey area.

A series of high-angle faults trends northwestward across the quadrangles. Most of the faults in the area are discontinuous, with some less than 1 km long; however, the Tularcitos fault zone continues across the entire mapped area. These faults displace the Monterey Formation and locally offset Quaternary deposits.

The onshore and offshore faults that have the same general orientation appear genetically related. First-motion studies of earthquakes in Monterey Bay (Greene and others, 1973, p. 7) indicate that the offshore faults are nearly vertical and that right-lateral, strike-slip displacement is occurring along these northwest-trending faults. Where exposed, fault planes of the northwest-trending onshore faults are steeply dipping, and the more westerly orientation of fold axes, especially those truncated by the Tularcitos fault, strongly suggests right-lateral displacement. First-motion studies also indicate right-lateral movement at depth on most of the faults in the study area.

FAULT GEOMETRY AND ACTIVITY

Ord Terrace Fault

Mapping. First mapped by Clark and others (1974) the Ord Terrace fault is a northwest-striking, steeply southwest-dipping reverse fault. The Ord Terrace fault separates Monterey Formation from Paso Robles Formation in the subsurface. The offshore extension of the Ord Terrace fault begins approximately 0.8 km to the northwest of the mapped area, but was not recorded on a more seaward seismic profile 2.4 km to the northwest (Clark and others, 1974).

Beneath the city of Seaside, abrupt changes in the subsea elevation of the top of the Monterey define a 2-km-long central fault section. In addition, three water wells (Ord Village #1, Playa #4, and Monterey Sand "Metz") near the mapped trace of the Ord Terrace fault reportedly produced hydrothermal ground water with temperatures of as high as 28°C. The presence of hydrothermal waters suggests that the offset of the Monterey Formation is due to faulting, rather than folding or erosion. Although subsurface data are limited, the southern section of the Ord Terrace fault extends 7 km southeastward into the Laguna Seca area as implied by truncated fold axes, and by offset subsurface structural contours on the Monterey Formation. The Ord Terrace fault appears to merge with the Chupines fault to the southeast.

Displacement. The logs of two wells approximately 215 m apart, the Luzern test well #5 (well 14, plate 1) and the now-abandoned Ord Village #1 (well 6, plate 1), indicate that the Ord Terrace fault vertically offsets the Monterey Formation by 198 m. Comparison of well logs on opposite sides of the Ord Terrace fault reveals that wells south of the fault have a slightly thinner section of Santa Margarita Sandstone than those north of the fault (Staal, Gardner & Dunne, 1990a, cross section A-A'). These data suggest that uplift on the Ord Terrace fault may have removed part of the Santa Margarita Sandstone before the Paso Robles Formation was deposited. Logs from boreholes on opposite sides of the fault show approximately 180 m of offset of the Paso Robles Formation (Staal, Gardner & Dunne, 1990a, cross section C-C').

Time of Movement. McCulloch and Greene (1989) show that the northern extension of the Ord Terrace fault cuts Pleistocene strata and offsets the sea floor. Offset of the Paso Robles Formation indicates post-early Pleistocene movement on the central part of Ord Terrace fault. No indication of offset Holocene strata is evident from interpretation of well logs. However, most well logs do not differentiate strata ranging in age from Pleistocene Aromas Sand to Holocene dune deposits and thus are of little value in bracketing the latest time of movement.

Seaside Fault

Mapping. As mapped in this study, the Seaside fault is a buried northwest-striking, steeply southwest-dipping reverse fault that separates Monterey Formation from Paso Robles Formation. Significant differences in depth to the Monterey and warm water in wells caused Newcomb [1941] to postulate a northeast-striking fault in the Seaside area.

Clark and others (1974) used subsurface structural contouring and the presence of a "sulfur hot spring" to map a northwest-striking fault beneath the city of Seaside. Subsequent research by John Logan revealed that the "hot spring" was hydrothermal water flowing from the abandoned deep East Monterey Hot Springs well (well 17, plate 1) into a shallow well drilled by Del Monte Properties. Regardless of the source, Clark and others (1974) reported that hot water continued to flow to the surface as late as the 1940's.

An offshore extension of the Seaside fault continues as far as 11 km to the northwest, where on seismic profiles it appears as a narrow, near-vertical fault zone (Clark and others, 1974).

Other evidence for an offshore fault is the report of a tremendous offshore explosion of gas and asphaltic oil that "brought up many hundred tons of peat" which lead to the 1902 drilling of an important wildcat well onshore near the explosion site (R.C. Newcomb, USGS, unpublished field notes, 1941). Although shows of oil and gas were reported, this well (East Monterey Hot Springs well) produced mainly sulfurous, artesian hot water.

Beneath the city of Seaside, abrupt changes in the depth to the Monterey define the 4-km-long central section of the Seaside fault. South of the fault, the Monterey Formation is typically less than 30 m deep, whereas north of the fault it drops off to over 200 meters. In addition, the hydrothermal waters from the East Monterey Hot Springs well support the presence of a fault. South of North-South Road, interpretation of well data suggests a possible 3-km-long southern segment of the Seaside fault that continues southeastward to connect with a northwest-striking splinter of the Chupines fault exposed in the foothills near the intersection of State Highway 68 and York Road.

Displacement. The logs of two now-abandoned wells approximately 670 m apart, the East Tioga #8 test well (well 20, plate 1) and the "Tom Philips" (well 47, plate 1), show that the Seaside fault vertically offsets the Monterey Formation by 133 m. These logs also show approximately 84 m of offset of the Paso Robles Formation (Staal, Gardner & Dunne, 1990a, cross section B-B').

Time of Movement. Although offshore oil and gas seepage support the presence of the offshore extension of the Seaside fault, it does not prove Holocene activity. McCulloch and Greene (1989) show that the offshore extension of the Seaside fault does not appear to offset Quaternary strata or the sea floor. Offset of the Paso Robles Formation indicates post-early Pleistocene movement on the Seaside fault. Because of the extensive cultural modification of the Seaside and Fort Ord areas, surficial evidence of Holocene faulting is lacking.

Chupines Fault

Mapping. The Chupines fault zone consists of several discontinuous northwest-striking faults crossing through the Carmel Valley, Corral de Tierra, Laguna Seca, and Seaside areas (Bowen, 1965, figure 2). Herold (1935) mapped the Buckeye fault as a 3-km-long fault extending southwest from Calera Canyon to the crest of the Sierra de Salinas. Fiedler (1944) extended the Buckeye fault another 4 km southwest to the head of Chupines Creek (Carmel Valley quadrangle) and named it the "Chupines fault." As mapped by Herold and Fiedler, the Buckeye segment is a northwest-striking, vertical fault that juxtaposes middle Miocene sandstone on the north against upthrown granodiorite on the south.

Herold (1935) mapped the Calera fault as truncating the Buckeye fault and continuing northwestward 8 km from Calera Canyon to Laureles Grade. The Calera segment places Monterey Formation on the north against older rocks (Monterey Formation, middle Miocene sandstone, and granodiorite) on the south. Near Robley Road (Spreckels quadrangle) a parallel branch of the Calera segment separates steeply dipping Paso Robles Formation from Monterey diatomite. This branch continues northwestward for 3 km where it is concealed beneath alluvium and joins the Seaside fault.

The 6-km-long segment begins at the westerly change in strike at the Hidden Hills subdivision and ends at State Highway 68, where it is concealed by alluvium (plate 3). The Hidden Hills segment includes two short west- to northwest-striking faults in the foothills south of Canyon del Rey originally mapped by Beal (1915). Clark and others (1974) showed these faults juxtaposing Santa Margarita Sandstone and Paso Robles Formation against Monterey diatomite. Along this segment, the dip of the fault ranges from 70° N. to 63° S. Bowen (1980) trenched across the Hidden Hills segment and found a 10-m-wide zone of fault gouge within gently dipping Paso Robles Formation (map locality 4, plate 3).

The Canyon del Rey segment of the Chupines fault continues northwestward for 5 km beneath the alluvium of Canyon del Rey toward Monterey Bay. Along Canyon del Rey, structurally high outcrops of the Monterey delineate the trace of the Chupines fault. Near the intersection of North-South Road and Canyon del Rey, steep dips in diatomite suggest nearby faulting. Because the Monterey Formation is structurally high between the Chupines fault and the Seaside fault, it was eroded during low stands of sea level. Because of this erosion, subsurface contours on the top of the Monterey Formation do not show significant displacement. The postulated northwestward extension of the inferred Chupines fault from to the offshore is suggested by the greater depth (approximately 54 m) at which the top of the Monterey was reached in the “Harcourt” well (well 40, plate 1).

The offshore section of the Chupines fault appears on a seismic profile 1.2 km offshore where the Monterey Formation is folded into a syncline that is faulted at depth. However, a second seismic track 0.6 km father offshore reveals only gentle northward dips in the Monterey on strike with this fault trend.

Displacement. Estimates of minimum vertical displacement on faults within the Chupines fault zone range from about 200 m (Fiedler, 1944) to 300 m (Herold, 1935). Sieck (1964) used gravity data to postulate about 300 m of vertical offset of the granitic basement with the northeast block downthrown. Large vertical displacements of Quaternary rocks along the Chupines fault are rare. Interpretation of well logs shows approximately 150 m of offset of the Paso Robles Formation (Staal, Gardner & Dunne, 1988a, cross section B-B'). However, Clark and others (1974) observed only 2 to 3 m of vertical offset of the Paso Robles at the surface, with the south side downthrown.

Much of the late Quaternary displacement along the Chupines fault may be strike-slip. In a trench across the northern section of the Hidden Hills segment (map locality 3, plate 3), Vaughan and others (1991) found “striated fault planes” and a vertical fault that “projects from two trench exposures to a right-deflected drainage, yielding a maximum horizontal slip rate of about 2 millimeters per year over the last 12,000 to 13,000 years.” Prominent saddles and linear drainages along the Hidden Hills segment provide additional geomorphic evidence for strike-slip displacement. Alternatively, field mapping and interpretation of aerial photographs suggest that these features could be part of large landslides.

Time of Movement. Stratigraphic evidence indicates minor post-Pleistocene movement on the Chupines fault, and other lines of evidence suggest Holocene activity. McCulloch and Greene (1989) show an offshore segment of the Chupines fault cutting Holocene strata and the sea floor. An earthquake epicenter nearly coincides with the fault described by Vaughan and others (1991), and three other epicenters plot within 1 km of the surface trace (plate 3). These data suggest that the Chupines fault is active.

Navy Fault

Mapping. The Navy fault was first mapped by Clark and others (1974) and described as a northwest-striking, steeply southwest-dipping strike-slip fault extending from Carmel Valley northwest to Monterey Bay. Local shearing, structural discordances, and the discontinuity of westerly-trending fold axes delineate the Navy fault, although the trace is locally concealed by alluvium and landslide deposits. Its near alignment with the mapped Tularcitos fault to the southeast and the similarity in trends strongly suggest that these two faults are continuous.

The southern section of the Navy fault begins at the mouth of Berwick Canyon. This zone of the fault is characterized by structural discordances across individual fault traces, locally sheared shale, and truncated en echelon fold axes in the Monterey Formation. A splay of the Navy fault is exposed in along Tierra Grande Drive about 0.5 km east of Berwick Canyon (map locality 9, plate 3). Here the fault vertically offsets a late Pleistocene fluvial terrace deposit by approximately 1 m with a reverse sense of separation (figure 3).

The Navy fault splits into two subparallel branches at the base of a northeast-facing scarp along Cañada de la Ordena. The two traces rejoin for a short distance in a linear valley near the head of Cañada de la Segunda, and then diverge again northwestward toward Monterey. Near where the faults rejoin, a splay of the Navy fault was exposed in an exploratory trench next to the water tank along the west boundary of sec. 10, T. 16 S., R. 1 E. (Wahler Associates, 1990). In this trench, a thin horizontal clay seam was vertically offset 30 cm by a normal fault oriented N. 47° W., 65° SW. The fault plane consists of a 30-cm-wide zone of crushed shale and does not appear to offset the overlying soil.

R.E. Johnson & Associates (1981) depicted the Navy fault as bifurcating around Flagg Hill (knob "469" southeast of the Del Monte Golf Course), rather than through Flagg Hill as depicted by Clark and others (1974). However, geologic evidence is lacking for extending their concealed western branch northward to Canyon del Rey. Mapping in this study suggests that the branch on the east side of Flagg Hill continues northward toward Monterey, whereas the branch on the west side of Flagg Hill is cut off by the Sylvan thrust fault.

Structural discordances in the Monterey and truncated fold axes suggest that the Navy fault continues northwestward to join an offshore fault, although this part of the fault zone could not be traced on the ground or on aerial photographs through the Quaternary deposits. Interpretation of well data indicates that this area is structurally high. This relief exposed the surface of the Monterey Formation to erosion during Pleistocene low stands of sea level. As a result, subsurface structural contours on the top of the Monterey Formation do not support or refute the presence of this faulting. However, an artesian well 365 m west of the mapped trace of the Navy fault at the Hotel Del Monte (now the Naval Post Graduate School) implies the presence of a fault. This 335-m-deep well was drilled in 1882 and reportedly produced lukewarm, brackish water (Elmer Lagorio, local historian, written commun., 1994).

Greene (1977) used seismic reflection profiling to map a 9-km-long offshore northern extension of the Navy fault. This offshore fault has Tertiary sedimentary rock downthrown on the northeast against granitic basement. However, high resolution profiles across the nearshore part of the fault show drag folds indicating the northeast side is upthrown (Greene, 1977).

Displacement. Several lines of evidence support strike-slip movement along the Navy fault. Well-defined geomorphic features such as linear drainages, aligned benches, and saddles are characteristic of strike-slip faults. Also, the presence of northwest-trending thrust faults and en echelon fold axes is consistent with transpression developed along a right-lateral strike-slip fault. Seismologic evidence includes one fault plane solution for the Navy fault that shows a combination of reverse and right lateral motion (figure 12). First motion studies also show right lateral strike-slip motion along vertical fault planes for the Monterey Bay fault zone (Cockerham and others, 1990).

Between two wells across the fault, the "Aguajito 1" well (well 70, plate 1) and the "Saucito" wildcat well 1 km to the southwest, the difference in elevation of granitic basement rock is 60 m. This difference is small compared to other regional reverse faults, suggesting that much of the displacement on the Navy fault is strike-slip.

Time of Movement. In a road cut approximately 0.1 km west of Berwick Canyon, late Pleistocene terrace sand beds dip 16° NE. into the fault, suggesting post-late Pleistocene movement along the Navy fault (map locality 8, plate 3). Trenching studies are inconclusive regarding Holocene activity. Three trenches excavated by Wahler Associates (1990) in a valley along the mapped trace of the Navy fault (sec. 10, T. 16 S., R. 1 E., Seaside quadrangle) revealed sandy clay colluvium containing angular shale fragments to the explored depth of 4 m. The trench logs show no offset of the colluvium. An adjacent large-diameter boring encountered 4.5 m of colluvium underlain by "crushed and sheared shale" to the explored depth of 18 m. Although these subsurface data suggest that the Navy fault is present, the trenches are not sufficiently deep to determine the nature of the colluvium/bedrock contact and the recency of movement along the fault at this location.

McCulloch and Greene (1989) mapped an offshore extension of the Navy fault as cutting Holocene strata and offsetting the sea floor. Along an offshore trace 9 km north of Monterey at a water depth of 90 meters, H.G. Greene (written commun., 1994) reports finding, "… uplifted, recemented Pleistocene gravel along fault. This feature is a northeast-trending anomalous dome-shaped mound approximately 80 m long, 40 m wide, and 4 m high."

Several earthquakes that plot near the Navy fault indicate continuing Holocene activity (figures 12 and 13). This does not imply that larger earthquakes could not occur along this fault zone. Indeed, Richter (1958) plotted two large earthquakes of magnitude 6.1 that occurred in 1926 as within the Monterey Bay fault zone, but these events may have been associated with movement along the San Gregorio fault zone.

Sylvan Thrust

Mapping. The Sylvan thrust fault consists of a zone of thrust faults that locally offset terrace deposits in the Monterey foothills. Clark and others (1974) mapped a 1.5-km-long thrust fault exposed on Sylvan Road as juxtaposing Monterey Formation against "older alluvium." Dupré (1990b) extended the Sylvan thrust fault 1 km east and showed it offsetting the 415 ka "Silvan" coastal terrace. We extended the Sylvan thrust an additional 0.5 km eastward based on exposures of steeply dipping, contorted Monterey Formation.

This extension joins the Navy fault southeast of Flagg Hill. On Olmstead Road, the Monterey Formation is tightly folded and intensely faulted, and a fault offsets a middle Pleistocene fluvial terrace by 10 m (Wright and others, 1990). At Flagg Hill, the Sylvan thrust juxtaposes the Paso Robles Formation against the Monterey Formation in 37-m-wide sheared and contorted zone.

Dupré (1990b) also mapped a "linear scarp of uncertain origin, possibly structurally controlled" for 2 km westward from the earlier mapped Sylvan thrust. In Monterey, new road cuts along Dupré's "linear scarp" expose folded terrace deposits (figure 5) and steeply dipping terrace deposits (figure 6) confirming this western extension of the Sylvan thrust.

Field checking of road cut exposures also revealed a parallel zone of thrust faults approximately 0.5 km south near Devil Hill. These thrust faults are characterized by contorted and sheared zones of Monterey shale up to 10 m wide. Locally, faults with small vertical displacements offset terrace deposits and colluvium.

Displacement. Field evidence suggests mostly reverse slip on the Sylvan thrust fault. The fault vertically offsets coastal terrace deposits by 15–20 m (Clark and others, 1974; Dupré, 1990b). Detailed logging of a recent (January 1993) road cut exposing the Sylvan thrust below La Mesa Elementary School reveals that a group of small faults offsets coastal terrace deposits and colluvium against Monterey shale by 1–2 m (figure 4).

However, seismologic evidence suggests that the Sylvan thrust has a component of strike-slip movement. During January 1976, a swarm of small earthquakes occurred in the vicinity of the

Sylvan thrust (figure 12). Most of these earthquakes have first-motion solutions that indicate right-lateral motion on steeply southwest-dipping planes. This is consistent with an uplifted block in a strike-slip fault zone in which sinuous faults splay from the main fault in "palm tree structure" (Sylvester, 1988, p. 1687).

Time of Movement. Quaternary deformation along the Sylvan thrust exists at several exposures. Middle Pleistocene coastal terrace deposits are faulted against Monterey Formation (map localities 8 and 9, plate 2). At the La Mesa School exposure (figure 4), an organic-rich silt layer in faulted colluvium yielded a ^{14}C age of 4,890±90 yr B.P. (appendix A) indicating Holocene movement. The January 1976 swarm of earthquakes also confirms that the Sylvan fault is active.

Tularcitos Fault

Mapping. First mapped by Fiedler (1944), the Tularcitos fault is a northwest-striking, steeply southwest-dipping reverse fault that separates Tertiary sedimentary rocks from Salinian basement rocks. Bowen (1965) correctly observed that the Tularcitos fault is not a single trace, rather a "… braided, imbricate system of many steeply dipping faults." The Tularcitos fault zone extends from the southern part of the Seaside quadrangle southeastward into the Jamesburg area, where it branches into the Paloma fault, a total distance of approximately 42 km.

The Tularcitos Creek segment begins approximately 20 km southeast of the study area near the head of Tularcitos Creek (Rana Creek quadrangle). Along most of this segment the fault is buried beneath Quaternary alluvium and landslide deposits, but is locally delineated by upthrown granitic basement rock on the southwest and Tertiary sedimentary rock on the northeast. Geomorphic features such as deflected drainages and linear closed depressions, visible in the field and on aerial photographs, delineate this part of the Tularcitos fault. On the north side of Tularcitos Ridge (northeast corner of projected sec. 20, T. 17 S., R. 3 E.) the Tularcitos Creek segment is exposed in a new road cut, with upper Pleistocene to lower Holocene debris flow deposits thrust against granodiorite along a fault that strikes N. 85° E. and dips 50° SE.

Farther west on Carmel Valley Road, two splays of the Tularcitos fault that dip 82° to 84° SW. offset colluvium and fluvial terrace deposits against Monterey shale (figures 7 and 8). The Tularcitos Creek segment ends near Camp Stephani, where the fault curves northwestward and splays out in the northwest corner of sec. 10, T. 17 S., R. 2 E. (Carmel Valley quadrangle). At this location, three subparallel near-vertical traces of the fault juxtapose granitic rock against Monterey Formation and Miocene marine sandstone along Southbank Road (Kingsley Associates, 1981). Field checking by Rosenberg (1993) found that these faults do not appear to offset overlying thin colluvial deposits. These three faults project beneath but do not appear to displace Pleistocene landslide deposits to the northwest at Robles del Rio.

The Mid-Valley segment of the Tularcitos fault is characterized by a 9-km-long main fault, and several subsidiary parallel faults. The main trace is concealed by alluvium from Carmel Valley Village to the west end of Garzas Road (Carmel Valley quadrangle). This portion of the fault was located by plotting bedrock lithology as interpreted by Logan (1983) from water well logs. Logs of wells completed after Logan's 1983 report were also interpreted to plot bedrock lithology. Wells completed in shale or sandstone are on the north side of the fault and wells completed in granite are on the south side. Water well logs and geophysical data also suggest a buried granitic bedrock high near the mouth of Juan de Matte Canyon.

The Mid-Valley segment is concealed by the Carmel River near Scarlett Road in an area known locally as "the narrows." The name "narrows" is derived from the abrupt constriction of the valley between granitic outcrops. Steeply dipping sandstone beds and "anomalously thick sandstone" found in a water well indicate faulting in this area (Richard R. Thorup, oral commun., 1986, as cited in McKittrick, 1987, p. 10). Logs of water wells drilled in the narrows reveal that the Tularcitos fault separates granitic bedrock from the Monterey Formation. The Mid-Valley segment ends near the mouth of Berwick Canyon, where it appears to join the Navy fault.

In the hills on the north side of the Carmel River is the Foothills segment of the Tularcitos fault. The Foothills segment begins near Sycamore Gulch (Carmel Valley quadrangle) where it branches northwestward from the Tularcitos Creek segment and continues northwestward for approximately 15 km (McKittrick, 1987). Steeply dipping, sheared Monterey Formation and vague tonal lineaments on aerial photographs mark this segment of the fault. From Laureles Grade westward to Tomasini Canyon, the Foothills segment aligns with and cuts the edge of the broad fluvial terrace mapped by Dupré (1990b). On Rancho Fiesta Road, a fluvial terrace is tilted 18 degrees toward the Tularcitos fault (map locality 11, plate 3; figure 9).

Extending along the foothills from the west end of Garzas Road (Mount Carmel quadrangle) to Garland Ranch Regional Park (NE1/4 sec. 30, T. 16 S., R. 2 E., Seaside quadrangle), is the Garland Park segment. The Garland Park segment is a zone of crushed granitic rock thrust over Miocene marine sandstone. This branch of the Tularcitos fault appears on aerial photographs as a series of topographic benches and saddles. A broad flat-lying terrace near the 500-foot contour in the NE1/4 sec. 30, T. 16 S., R. 2 E. (Seaside quadrangle) appears to be a result of uplift along the Tularcitos fault. However, plowing of the terrace surface obscures any possible geomorphic evidence of recent faulting. Four springs lie near the Tularcitos fault in Garland Park (Nikki Nedeff, Monterey Peninsula Regional Park District, written commun., 1991). These springs emanate from the intensely fractured rock within this fault zone. Drainages that cross the Garland Park segment of the Tularcitos fault are not laterally offset, suggesting that recent strike-slip displacement has not occurred on this segment.

Clark and others (1974) depicted the Garland Park segment as striking westward near Snivelys Ridge where it is truncated by the northern extension of the Piñon Peak fault (the Snivelys fault of Bowen, 1965). Exploratory trenching did not reveal the presence of this segment of the Tularcitos fault (Earth Systems Consultants, 1984). Also, magnetometer and seismic refraction studies by O'Rourke (1980) fail to show evidence for this segment of the fault. Field checking of new road cuts at Carmel Valley Ranch (NW1/4 sec. 30, T. 16 S., R. 2 E.) by Rosenberg (1993) confirmed mapping by Clark and McKittrick (1985) showing that the granite/sandstone contact is an unconformity, rather than a fault.

Displacement. Total post-Miocene vertical displacement of the Tularcitos fault is about 380 m (Fiedler, 1944, p. 237). Because of stream erosion and landsliding, evidence of Quaternary displacement is limited. However, detailed logging of the Carmel Valley Road exposure revealed approximately 1 m of offset of the terrace deposits and overlying colluvium (figure 8).

Graham (1976, p. 151) postulated that at least 3.2 km and possibly 16 km of right-lateral displacement has occurred along the Tularcitos fault, based on the apparent offset of distinctive beds in the Monterey Formation. Other evidence of strike-slip displacement includes two earthquake focal mechanisms indicating right-reverse-oblique-slip movement on the Tularcitos fault (figure 14 and appendix A).

Time of Movement. Although much of the Tularcitos fault is poorly exposed, two exposures suggest Holocene movement. At the Carmel Valley Road exposure (figure 8), an offset organic silt horizon in the colluvium yielded a ^{14}C age of 7,780±160 yr B.P. (appendix A). At the Rancho Fiesta Road exposure (figure 9), the fault trace is concealed by a debris flow; however, the base of the colluvium appears offset along the fault. Clustered epicenters that align with the Tularcitos fault indicate that it is active.

Berwick Canyon Fault

Mapping. Beal (1915) originally mapped, but did not name, two short, en echelon, northwest-striking faults near Berwick Canyon. Clark and others (1974) mapped three en echelon faults as the Berwick Canyon fault. The Berwick Canyon fault extends northwestward from the Carmel River about 5.5 km to the Monterra Ranch, and locally offsets Pleistocene terrace deposits. McKittrick (1987) mapped a 35-m-wide zone of near-vertical dipping Monterey Formation extending for 2 km along the Berwick Canyon fault.

The main trace of the Berwick Canyon fault is defined by intensely fractured, steeply dipping Monterey shale in an area of otherwise gently folded beds. On topographic maps and aerial photographs, the fault appears as a series of aligned linear drainages and poorly developed topographic benches and saddles. The Berwick Canyon fault appears to have sheared and offset Pleistocene terrace deposits (map locality 10, plate 3).

Clark and McKittrick (1985) inferred a west-striking extension of the Berwick Canyon fault that connects with the Navy fault along a well-developed linear drainage parallel to the ridge crest. However, no fault-related features are present to support the presence of this inferred trace. Clark and McKittrick (1985) speculated that the Berwick Canyon fault continues northwestward toward the Chupines fault. Offset fold axes and possible fault-related features in trenches at Monterra Ranch support this extension of the eastern segment.

Displacement. The dip of the fault is probably near-vertical to steeply dipping with a reverse sense of displacement, based on the geometry and relationship to nearby faults. The total amount of displacement is not known, although Younse (1980) shows approximately 90 m of vertical offset along the Berwick Canyon fault.

Time of Movement. Offset terrace deposits demonstrate post middle-Pleistocene movement on the Berwick Canyon fault (map locality 10, plate 3). Vaughan and others (1991) logged an exploratory trench on Monterra Ranch across the projected fault trace and found offset colluvial wedges. Radiocarbon dating of the colluvium indicates two or three episodes of movement during Holocene time. Rosenberg (1993) examined the trench exposure and concluded that the source of the colluvial wedges was equivocal and alternatively could result from landsliding.

Laureles Fault

Mapping. The Laureles fault was first mapped by Herold (1935) in the southwest corner of the Spreckels quadrangle. Fiedler (1944) extended the Laureles fault southeast into the Carmel Valley quadrangle, and renamed it the Del Monte fault for an exposure near Rancho Del Monte (now the Los Laureles Lodge). In this report, the original name “Laureles” is retained to avoid confusion with faults near the Del Monte district of Monterey.

The length of the Laureles fault is approximately 6.5 km. Steep to near-vertical dipping Monterey Formation shale locally offset against Pleistocene terrace deposits characterizes the northwest portion of the Laureles fault from Tomasini Canyon to Laureles Grade. An anomalously thick section of Miocene marine sandstone was encountered in a water well adjacent to the south side of the Laureles fault about 150 m west of Laureles Grade. Granite was not penetrated to the depth of 176 m, although it crops out nearby on the north side of the fault (R.R. Thorup, oral commun., 1992).

From Laureles Grade to Carmel Valley Village (Carmel Valley quadrangle), the fault separates Salinian basement on the north from steeply dipping middle Miocene marine sandstone. Northeast of Carmel Valley Village, the Laureles fault continues eastward into a large landslide deposit and dies out. Fiedler (1944) showed the Laureles fault terminated by a cross-fault; however, field evidence and analysis of aerial photographs do not support his interpretation.

Displacement. Herold (1935) described the Laureles fault as a northwest-striking, vertical fault separating Cretaceous granitic rock and Miocene marine sandstone. Fiedler (1944) showed the Laureles fault as a southwest-dipping normal fault, whereas Dibblee (1972) mapped the Laureles fault as high-angle reverse fault dipping 75° NE. Estimates of vertical displacement on the Laureles fault range from about 180 m (Fiedler, 1944) to 300 m (Herold, 1935).

Time of Movement. Clearly offset Quaternary deposits are limited along the Laureles fault. On a spur ridge approximately 120 m west of Juan de Matte Canyon, an en echelon segment of the Laureles fault offsets a small patch of Pleistocene fluvial terrace gravel (map locality 12, plate 3). However in 1993, grading destroyed most of this exposure. This limited exposure suggests the latest movement on the Laureles fault is probably Holocene.

Snively Fault

Mapping. Brown (1962) mapped a northwest-striking fault on the southwest side of Snivelys Ridge separating granite and sandstone. This fault appears to be the northern extension of the Piñon Peak fault of Trask (1926), which Bowen (1965) named the Snively fault. The combined length of the Piñon Peak and Snively faults is approximately 4 km.

O'Rourke (1980) used exploratory borings and magnetometer data to extend the Snively fault north beneath the large landslide in the NE1/4 sec. 25, T. 16 S., R. 1 E. Rosenberg (1993) field checked 10-m-deep dozer excavations within the landslide area and found no Quaternary evidence for the concealed portion of the Snively fault mapped by O'Rourke (1980) and Clark and others (1974).

Displacement. The Piñon Peak/Snively fault has approximately 210 m of reverse throw, and separates Miocene sedimentary rock from granitic basement rock (Trask, 1926). O'Rourke (1980) described the fault as a 30-m-wide, near-vertical zone of sheared granodiorite, with a vertical offset of 95 m.

Time of Movement. On aerial photographs, the fault appears as a prominent linear feature flanked by several landslides. Quaternary landslide deposits along the fault zone within the study area are not offset by the Piñon Peak or Snively faults.

Hatton Canyon Fault

Mapping. Beal (1915) and Galliher (1930) showed, but did not name, a group of northwest-striking, near-vertical dipping reverse faults that offset Monterey shale against Pleistocene terrace deposits in Hatton Canyon. The Hatton Canyon fault extends 11.5 km northwest from Carmel Valley Road to Point Joe on the coast.

The southern segment of the Hatton Canyon fault begins near Valley Greens Drive and Carmel Valley Road. The southern segment continues northwestward approximately 4 km to Hatton Canyon and is marked by intensely fractured, steeply dipping Monterey Formation in an area of otherwise gently dipping beds. On Carmel Valley Road, the fault offsets landslide and terrace deposits (map locality 6, plate 3).

Along the projected trend of the southern segment is a hydrogeologic barrier at the September Ranch (map locality 5, plate 3). Faulting is suggested by the high yield of the 1931 "Hatton" well drilled within the fault zone (63 dm^3/s, Roy Alsop, Sr., oral commun., as cited in Thorup, 1976, p. 8), and the low yield of adjacent wells outside the fault zone (Meffley and Brown, 1974). Alternatively, this hydrogeologic barrier could be an ancestral channel cut into shale bedrock (D.K. Todd, 1985, as cited in Oliver, 1991, p. 2). However, driller's logs for the Hatton well and the adjacent 1990 "September Ranch" well record a sequence of shale underlain by sand and gravel, which in turn is underlain by shale. The repeated section of shale indicates reverse faulting, and does not support the ancestral channel interpretation.

The Water Tank segment is a discontinuous 30-m-wide zone of steeply dipping and intensely fractured shale that offsets lower fluvial terrace deposits. It begins near Hall School and continues northwestward approximately 4 km to Pacific Meadows where it merges with the southern segment. North of the inactive Sierra Quarry, the fault has rotated terrace deposits (map locality 7, plate 3).

In 1991, a construction excavation at Pacific Meadows revealed a critical exposure of the Water Tank segment (figure 10). At this location, the fault clearly offsets Monterey shale against an upper level fluvial terrace deposit and landslide deposits (map locality 12, plate 2). Colluvium overlying the fault thins abruptly on the upthrown side of the fault; however, the fault strand is obscure within the colluvium. Upp Geotechnology (1991) later excavated an exploratory trench 20 m east of this exposure. The trench exposed near-vertical dipping terrace deposits faulted against steeply dipping shale beds and landslide deposits in a 3.6-m-wide zone of faulting.

The central segment of the Hatton Canyon fault extends from Jacks Peak Regional Park and follows a curvilinear trace to State Highway 1. About 1 km east of Hatton Canyon, gently folded fluvial terrace deposits above the mapped trace of the fault are cut by near-vertical clay-filled fractures that strike approximately N. 60° E. (map locality 11, plate 2). A year-round spring flows where the fault crosses the head of Hatton Canyon.

The northwestern segment of the Hatton Canyon fault extends 5 km northwestward from State Highway 1 to Point Joe. Although exposures are poor in the densely vegetated canyons, discordant structural attitudes and prominent aligned linear drainages suggest faulting. The northwestern segment may continue offshore as a series of short faults mapped by H.G. Greene (oral commun., 1994).

Displacement. The total displacement along the Hatton Canyon fault is unknown, but similar terrace deposits located about 120 m south of the Water Tank segment are approximately 30 m lower in elevation. This suggests at least 30 m of vertical offset during Quaternary time. Several strands of the Water Tank segment also offset landslide and colluvial deposits by 15 to 30 cm (Rosenberg, 1993).

Time of Movement. Dating of offset colluvium yielded a ^{14}C age of 2,080±40 yr B.P. on the Water Tank segment (appendix A). Faulted landslide deposits at Pacific Meadows suggest Holocene movement. Also suggestive of Holocene activity is the hydrogeologic barrier at September Ranch. Recent activity is indicated by several earthquakes that align with the Hatton Canyon fault (figure 12).

Cypress Point Fault

Mapping. In describing the structural relationship of beds of the Paleocene Carmelo "Series" to the granodiorite at Pescadero Point, Lawson (1893, p. 20) states "Here at a small cove on the east side of the point they abut squarely on the granite, having been let down against it by a sharp fault." Bowen [1969] mapped this fault from Pescadero Point 3 km northwestward to Cypress Point and showed the northeastern side as relatively downthrown. More recent work by Dupré (written commun, 1989) delineates three en echelon faults at Fan Shell Beach with possible right-lateral, strike-slip displacement.

Seismic profiles offshore indicate that the Cypress Point fault extends northwestward from Cypress Point for about 3 km as a single continuous fault, and continues for another 3 km to the southern wall of Monterey Canyon as a zone of discontinuous, en echelon faults. The fault is identified in the seismic reflection profiles principally from juxtaposition of sediments of questionable Pleistocene age against granodiorite and from linear topographic expressions on the sea floor.

Simpson (1972) used subsea outcrops to extend the Cypress Point fault from Pescadero Point southeastward across Carmel Bay to join the fault at the headland south of Carmel (Carmel Point). At Carmel Point vesicular carmeloïte flows and carmeloïte flow breccias are faulted against Cretaceous granodiorite to the southwest in a 4 to 7-m-wide brecciated zone. However, in May 1993, severe beach erosion revealed a 60-m-long exposure of the fault striking N. 50° W., implying that the faults at Pescadero Point and Carmel Point are en echelon segments rather than continuous.

Clark and others (1974) showed the Cypress Point fault continuing southeastward across Carmel Point, where it was concealed beneath Quaternary sediments, and postulated that it separated carmeloïte mapped at the mouth of the Carmel River by Lawson (1893), but no longer exposed, from presumably granitic basement to the southwest. Exploratory drilling in the parking lot of Carmel River State Beach encountered carmeloïte at an elevation of 0.6 m, striking Lawson's "lost outcrop" (Staal, Gardner & Dunne, 1989).

As presently mapped, the Cypress Point fault strikes northwest-southeast for as much as 12 km. Field work by Clark (1989) on the Palo Corona Ranch and along San Jose Creek canyon to the southeast failed to reveal any significant structural or stratigraphic discordances that would permit the extension of this fault southeastward to San Jose Creek canyon and its possible continuation to the Blue Rock/Miller Creek fault zone as delineated by Ross (1976).

Displacement. The main strand of the Cypress Point fault juxtaposes the Carmelo Formation with granodiorite at Pescadero Point and carmeloïte with granodiorite at Carmel Point, suggesting that the northeast side is relatively downthrown. Clark (1989) believed the actual amount of dip-slip separation may be less than 20 m; whereas, exploratory drilling and seismic profiling suggest a vertical displacement of as much as 30 m (Staal, Gardner & Dunne, 1989).

Several lines of evidence suggest right-lateral displacement on the Cypress Point fault. Dupré (written commun., 1989) has postulated right-lateral strike-slip displacement east of Cypress Point. The relatively straight trend, its en echelon character, and the parallelism of this fault to the faults of the Monterey Bay fault zone, on which first-motion studies indicate right-slip, support this interpretation.

Time of Movement. Clark and others (1974) suggested that movement along the Cypress Point fault occurred before the Quaternary. East of Carmel Point, however, the terrace platform surface appears to be more than 1 m higher above the carmeloïte northeast of the fault than on the granodiorite to the southwest. This apparent elevation difference could have resulted from late Quaternary movement, as Dupré (1990a) has suggested an age of about 100 ka for this lowest terrace. Alternatively, this elevation difference across the fault could result from deposition on an irregular platform surface. McCulloch and Greene (1989) show the offshore segment of the Cypress Point fault cutting Quaternary strata.

QUATERNARY DEFORMATION

General Statement

Several lines of geologic evidence indicate ongoing tectonic deformation in the greater Monterey area. These include faulted, folded, and tilted Pleistocene terrace deposits; faulted Holocene colluvium; and earthquake epicenters that align with mapped fault traces.

Structural Framework

Data from field investigations, test wells, and earthquake distribution, permit an interpretation of the tectonic framework. The Tularcitos/Navy fault is the dominant through-going fault in the study area. Microseismicity data suggest that the Tularcitos/Navy fault extends to nearly 14 km depth. En echelon faults such as the Laureles appear to branch off at shallower depths (figure 14).

Depth to basement increases northeastward across each block of the zone between the Chupines, Seaside, and Ord Terrace faults. One interpretation is that these faults are imbricated and splay off the Chupines or possibly the Navy fault (figure 13). This is consistent with an uplifted block in a strike-slip fault zone in which sinuous faults splay from the main fault in “palm tree structure” (Sylvester, 1988, p. 1687).

Folding and Tilting

Two types of folds are common in the study area: (1) very tight and broken folds such as those occurring in the Monterey Formation adjacent to fault zones, and (2) much broader, open folds that are mappable on a larger scale (plates 1, 2, and 3). Dips typically are vertical or overturned within the fault zones, with drag folds common. The regional fold axes are oblique to the trend of the through-going faults and trend mainly N. 65°–85° W. Most of these major folds are subparallel to faults (N. 40°–50° W. trend) and are truncated by faults, indicating that folding was penecontemporaneous with strike-slip faulting.

The number and intensity of folds increase between the Chupines fault and the Hatton Canyon fault. This is especially evident in the zone between the Sylvan thrust and the Hatton Canyon fault. In this zone of deformation, isolated terrace remnants dip approximately 10 degrees. The distribution of earthquakes suggests that this deformation is caused by movement on these and related faults at depth, including an inferred blind thrust fault (figure 12).

Folding and tilting of Quaternary deposits is evident at several places. Northeast of the Chupines fault, outcrops of the Paso Robles Formation dip as much as 20 degrees along the paired anticline and syncline south of Laguna Seca. Similarly, in the Seaside area, subsurface marker beds in the Paso Robles Formation dip almost 28 degrees along the anticline northeast of the Ord Terrace fault (Staal, Gardner & Dunne, 1990a, cross section C-C').

Younger terrace deposits are folded and faulted along the trace of the Sylvan thrust fault, although soft-sediment deformation is an alternate explanation locally (figure 5). Gently folded and fractured terrace deposits are exposed above the mapped trace of the Hatton Canyon fault (map locality 11, plate 2). These two examples imply post-middle Pleistocene deformation.

Tilted terrace deposits ranging in age from early to late Pleistocene are exposed in the Monterey and Carmel Valley hills. North of Huckleberry Hill (map locality 13, plate 2), an early Pleistocene terrace is tilted approximately 13 degrees. On the north side of the Carmel River, the youngest and lowest fluvial terraces are tilted as much as 22 degrees (map localities 7, 8, and 11;

plate 3). Because these tilted terraces are adjacent to faults and untilted terraces are exposed elsewhere, the tilted terraces represent local deformation rather than regional uplift.

Faults and Displacement Rates

Most of the faults in the study area cut Quaternary deposits, and the Tularcitos, Hatton Canyon, and Sylvan faults offset Holocene colluvium. The amount of displacement is easily measured; however, the absolute ages of most deposits are uncertain. A framework for determining the relative ages of the Quaternary deposits is outlined by Dupré (1990a). Dupré estimated ages of Monterey terraces by correlating these terraces with known sea level highstands and radiometrically dated terraces in Santa Cruz (table 1). Combining these field measurements and age estimates yields preliminary displacement rates for the faults (table 2).

Quaternary vertical displacement rates range from 0.01 mm/yr (Cypress Point fault) to 0.41 mm/yr (Sylvan thrust fault) and average about 0.11 mm/yr. This average rate is slightly lower than the 0.18 uplift rate for the Monterey area estimated by Dupré (1990a). This probably reflects that fault displacements represent episodic uplift, whereas sea level curves represent long-term rates. The rugged topography in the study area also indicates relatively high long-term uplift rates.

Of the faults in the study area, the Sylvan thrust has the highest rate of uplift and the greatest number of recorded earthquakes. This high rate of uplift is related to transpression between the Hatton Canyon and Navy faults (figure 12). The density of fold axes between these faults supports active folding as an explanation for the high uplift rate on the Sylvan thrust fault.

The vertical slip rate of the Navy fault is anomalously low at 0.02 mm/yr. This corroborates the first-motion and geomorphic data indicating lateral displacement. Alternatively, the apparent lack of vertical displacement could result from stripping of Quaternary deposits during lower stands of sea level.

Quaternary horizontal displacement rates are difficult to calculate because of the absence of suitable markers. Local erosion rates are rapid; as a result, features that could be used for estimating horizontal displacement are lacking. The only estimate of horizontal displacement on local faults is the 2 mm/yr cited by Vaughan and others (1991) for the Chupines fault.

Alternatively, the lack of visible horizontal surface displacement can be explained using the strain partitioning model of Lettis and Hanson (1991). In their model, “oblique strain in the lower lithosphere may partition upward in the brittle crust into nearly pure strike-slip and dip-slip deformation, the dip-slip component being expressed as reverse faults and folds.” This model accounts for the strike-slip sense of displacement indicated by focal-plane mechanisms and for the observed reverse stratigraphic displacement near the surface. The implication of this model is that short faults such as the Sylvan thrust fault are the upper crustal expressions of a seismic zone at depth.

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